ANALYSIS OF ENERGY EXCHANGE IN SYSTEM WITH VARYING MATERIALS AND CONDITIONS

Change in behaviour with different layouts

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Abstract

The main purpose of this research is to observe the behaviour of heat exchange in a controlled environment with varying conditions of materials and properties of the system. To achieve this objective, a heat exchanger with pipes of two different materials has been used, the two materials being glass and silicon carbide (SiC).

The experiment consisted in having two simultaneous currents going in opposite directions, a liquid current of water going through the pipes and gaseous current of atmospheric air running on the outer part of the exchanger. These two currents have very different initial temperatures (a difference of about 40 ºC), inducing the appearance of a heat flow in the direction of the cold current, in this case the liquid one.

We plan to observe and study how the change of material acting as separation between the currents can influence the system, analysing the parameters responsible for the changes in behaviour.

Figures and tables index

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Objectives

Main objectives

- Find out which parameters are the ones that have a biggest influence over the system and the outcome in terms of heat exchanged
- Note the differences between the two materials used as tubes
- Determine the best material to use as tube component and quantify the difference between both
- Determine the optimal set of conditions to achieve the maximum heat transfer between fluids
- Explain reasonably the results obtained and initiate a discussion about the outcome and its implications
- Provide enough evidence and data to support the conclusions on the outcome

Secondary objectives

- Design a flux diagram to use throughout the entirety of the process
- Establish several real cases in which each of the systems could be used with success considering surrounding conditions

Theoretical concepts

Heat transfer

The main concepts applied in the development of this project are the principles of heat transfer, consisting in the exchange of thermal energy between physical systems. In this case, the physical systems are two fluids, air and water separated. Heat transfer can be achieved following a variety of mechanisms, including thermal convection, thermal radiation, energy transfer by change of phase and by thermal conduction.

This last one, thermal conduction, is usually referred to as diffusion. Diffusion consists in the exchange of energy to the microscopical level through the boundary that separates the systems affected. When two bodies are in contact and find themselves at different initial temperatures, there tends to appear a heat flow that levels the temperatures of both systems. When these bodies reach the same temperature, it is said they reached thermal equilibrium. This heat flow always takes place in the direction of the lowest temperature system, as stated in the second law of thermodynamics. It is impossible to induce an energy transfer from a fluid that is at a lower temperature than the system that is supposed to be heated, as represented in the following figure.

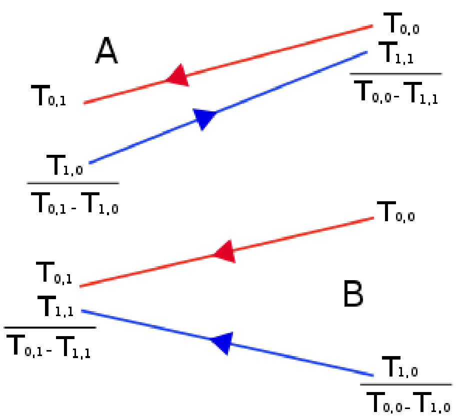

Figure 1. Diagram representing heat exchange between two currents. Counter current (A) and parallel flows (B)

As seen in the picture, the diagram representing the heat exchange between two currents can take two different forms, corresponding to counter current or parallel flow systems. But as can be observed, the two heat lines never cross each other, meaning the temperature on the cold current never gets to the temperature of the hot current. Otherwise, the energy transfer would be interrupted, reaching the point of thermal equilibrium.

This heat transfer by conduction is dictated by the thermal conductivity of the material forming the boundary between the two systems. This thermal conductivity is an intrinsic parameter of the material and can be evaluated quantitatively in terms of Fourier's Law.

Fourier's law establishes that "the heat transfer's rate through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient through which the heat flows". In its differential form, the equation is the following:

$$q = -k\nabla T$$

Where q represents the local flux density (W/m^2), k represents the material's conductivity (W/m·K) and ∇T is the temperature gradient (K/m). k is usually taken as a constant parameter, but in most cases there's a slight variation in its value, that changes with the temperature of the material, although this variation tends to be very small, thus making it normal to take it as a constant using its value in standard conditions. It is important noting that this is not the case for all materials and/or conditions.

For simple applications, Fourier's law is usually expressed as a one-dimensional equation in the x direction:

$$q_x = -k\frac{dT}{dx}$$

This same equation can also be expressed in its integral form in the following way:

$$\frac{Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$$

This form of the equation considers the amount of heat transferred after a certain period of time (Q/Δt) given a certain area (A).

Another way of heat transfer is through convection. This way of energy exchange is mainly induced by the movement of fluids. This form of energy transfer is usually the main one in fluids. Convection is considered to involve heat diffusion and advection processes, advection referring to the heat transfer provoked by bulk fluid flow.

Heat transfer by convection can be forced artificially by movement of fluids. An example of this system would be a pump in an aeroplane's engine. Convection can also be forced by fluid expansion.

As said before, convection happens mainly due to motion of the fluid, meaning that at any given point in time molecules of the fluid are moving together. This movement of particles, added to the existent temperature gradient, contributes greatly to heat transfer. The contribution to heat transfer by convection can be calculated through the following relation:

$$Q = hA(Tf - T)$$

Where Q represents the amount of heat transferred per time (W), A represents the area of the object (m), h heat is the heat transfer coefficient (W/m^2·K) intrinsic to the system, Tf represents the fluid temperature and T stands for the object's surface temperature.

In the case studied in this project, there is no heat transfer due to radiation and there are no phase changes, thus all heat transferred can be attributed to thermal conduction (diffusion) or thermal convection.

Heat exchanger

A heat exchanger is a device specially designed with processes of thermal exchange between two or more fluids in mind. In most cases, the fluids are separated by a solid layer of varying materials with different intrinsic properties. In other cases, the fluids may be in direct contact.

Heat exchangers usage is not even remotely limited to laboratory scenarios, being used daily and even unknowingly by a large part of the population, in the form of refrigerators, power stations, heaters or others.

Heat exchangers are mainly classified in two categories depending on their flow disposition. **Parallel-flow**, where the two fluid currents enter the device at the same end and travel in parallel disposition through the entirety of the circuit until the opposite end. This corresponds to the below diagram in figure 1. **Counter-flow**, where the case is the other way around. The two currents go into the device at the opposite ends, which corresponds to the above diagram in figure 1. This type of disposition is the most efficient in terms of being able of achieving a greater energy transfer due to having a higher temperature difference between fluids along the way.

When designing heat exchangers, the main factors considered are the surface are of the layer between the two fluids and resistance to fluid flow through the device, trying to maximize the first parameter while minimizing the resistance. In many cases, fins are added to the surface with the objective of increasing the effective area of contact, thus increasing the amount of heat that can be exchanged.

There are many different possible designs for heat exchangers, depending on the conditions and objectives necessary for the device. The most popular design and the one that is the focus of this research is the shell and tube heat exchanger (figure 2).

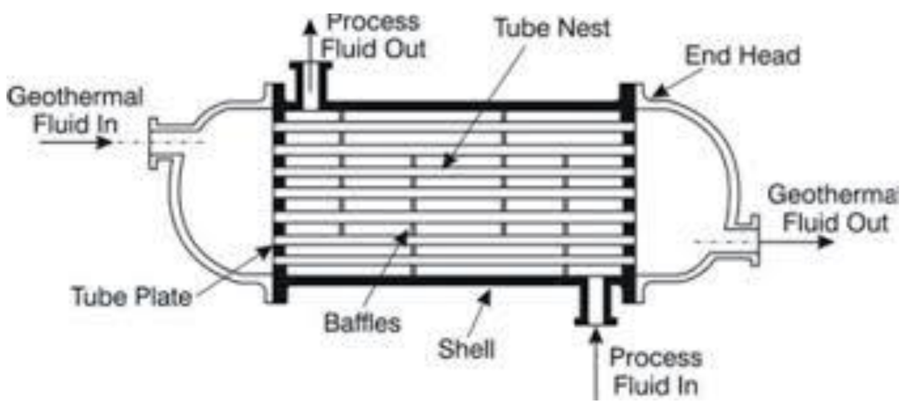

Figure 2. Shell and tubes heat exchanger

Other designs may include the use of a plating system or intermediate fluids that act as refrigerators or security devices.

The shell and tube design for a heat exchanger consists in a series of tubes that go through a shell. Inside the tubes a fluid flows, and this fluid must be heated or cooled. This is achieved by making a second fluid run through the shell, but outside the tubes, with a temperature difference big enough to induce a heat flow towards the coldest fluid. The material of which the tubes are made is important due to its heat transfer properties, potentially determining the capacity of heat transfer the device can achieve. This has led to the design of heat exchangers with different sets of tubes of varying materials, to establish comparisons and making studies about efficiency at different sets of conditions.

Shell and tube heat exchangers in the industry are mainly used for high-pressure applications, usually above 30 bars or really high temperatures. There are a lot parameters to take into account when designing and exchanger of this conditions, like tube diameter and thickness, length, corrugation or layout, because all of this parameters can greatly influence the outcome of energy exchanged or can help prevent undesirable events like corrosion or degradation of the device depending on the use it is going to get.

There are a lot of variations on the design of the shell and tube heat exchanger, some of them presented here:

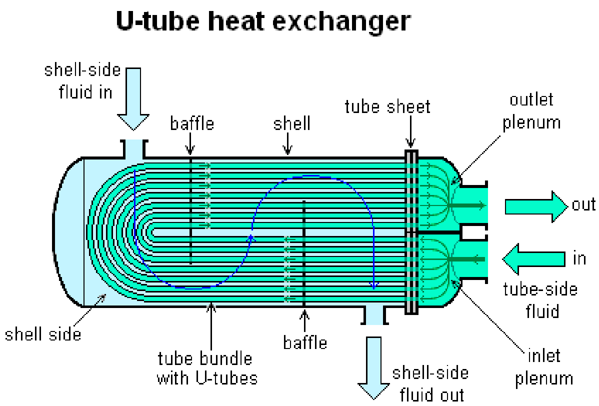

Figure 3. U-tube design

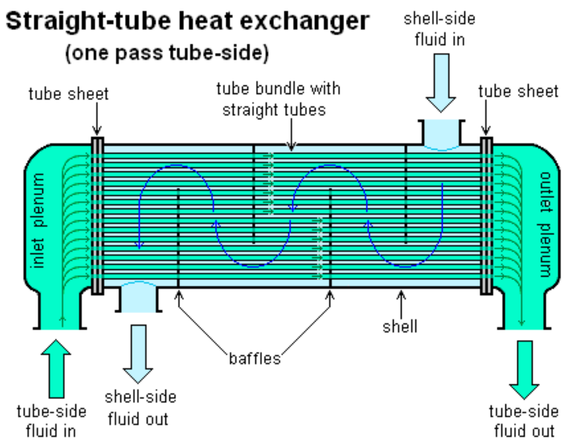

Figure 4. Straight-tube design

This last one is the design corresponding to the heat exchanger used in this research.

Methodology

A simplified flux diagram of the followed process can be seen below:

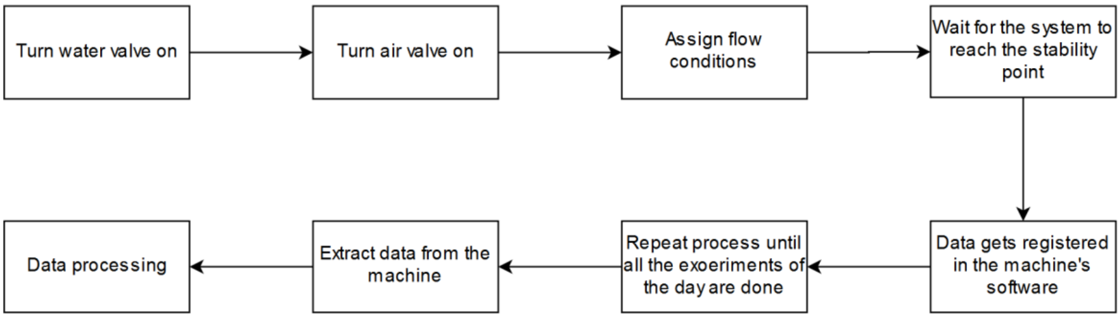

Figure 5. Flux diagram

The first step of the process after turning the machine on is opening the water valve. This water comes from a tank located in the basement of the building, which is has two cooling machines attached making sure the temperature inlet does not exceed 5 ºC, although there has to be a permanent control to assure the temperature does not get below 0 ºC, where freezing would start to happen thus influencing the outcome results.

Secondly, the air valve is turned on. This is atmospheric air, so standard properties for atmospheric air apply and are considered constant throughout the whole research.

After both flows are going, those need to be set through a frequency adjuster. Worth noting is that when tried to apply a really low frequency, the cooling system overrides the process and the inlet of water tends to go below 0 degrees, so there needs to be caution in this sense.

After all the conditions are set, the system takes about 5 minutes to adjust and get to a stability point. Once achieved this, the machine is kept going for about 5 minutes, during which all the temperatures, humidity and flows data is recorded in the SD card present in the computer.

The file on the SD card is permanently being overwritten, so all the experiments can be done in sequence with no need of stopping. It is important to keep a manual record of when each experiment is being conducted to be able to read the data afterwards.

After all the previous steps are done, the SD card can be extracted, where all the data from the experiments will be found for later processing. The end results are presented in tables in the results section or in the attached excel files.

Previous considerations and restrictions

Before talking about the results obtained, it is important to talk about the limitations of the research and the restrictions applied to it.

For starters, the variables that have been worked with are mainly 3, those being the liquid flow, the air flow and the initial temperature of the inlets. The flux velocity and atmospheric pressure experimented slight variations but in a small range, so these variables have been considered of constant value.

Another restriction applied is concerning the materials parameters. Specific heat changes with temperature, but the temperature range in which the research has been conducted is also considered small enough for this parameter to experiment a noticeable change, so it has also been considered a constant. The same goes for density.

On a final note, the flow has been considered to be composed entirely by homogenous fluids at any point, so the same composition is assumed in every point of the fluid's flow.

Concerning the experiments themselves, the ones with a liquid inlet below 0 ºC or with a theoretical efficiency over 100% have been discarded from the used data. In the case with water inlets below 0 degrees, the experiments have been discarded due to the possible presence of freezing, which could affect the end results. On the ones exceeding the 100% efficiency mark, it is obvious that the cold current can't absorb more heat than the transmitted by the hot current, meaning there must be some sort of data mistake, rending the experiment invalid.

Results

Glass

A total of 50 experiments have been conducted using the glass pipes. A table containing all the experiments is presented next, excluding the ones discarded:

Table 1. Experiments conducted with glass pipes

Nº	Air flow (Nm^3/h)	Volume flow (L/min)	Liquid in (ºC)	Liquid out (ºC)	Air in (ºC)	Air out (ºC)	Efficiency (%)
5G	108,14	388,67	0,07	0,27	46,20	28,00	12,85
6G	172,42	390,94	0,14	0,36	45,90	28,00	18,21
7G	175,99	307,71	1,04	1,28	46,20	28,00	22,01
8G	111,03	309,12	0,06	0,26	46,10	28,00	16,50
9G	169,47	389,23	2,26	2,45	46,30	26,90	22,56
10G	174,52	183,62	2,71	2,97	45,90	26,80	35,44
13G	167,49	28,84	1,65	2,58	41,60	26,50	47,86
14G	136,76	318,14	2,71	2,95	45,00	24,50	18,64
15G	139,27	310,47	2,03	2,22	44,40	23,90	24,56
16G	108,79	311,86	1,35	1,53	44,00	23,40	20,26
17G	176,15	266,78	1,40	1,61	44,20	23,20	33,51
18G	141,61	264,31	1,26	1,48	44,20	23,10	26,08
19G	107,60	265,09	0,71	0,92	43,90	22,90	20,60
20G	175,15	154,36	0,66	0,97	44,40	22,70	40,31
21G	141,05	157,78	0,78	1,10	44,20	22,30	31,05
22G	106,51	156,99	0,01	0,28	44,80	21,80	29,33
23G	174,82	42,45	1,44	2,18	44,70	21,20	66,37
24G	140,72	392,92	1,16	1,36	43,70	20,00	21,54
25G	105,02	389,25	2,38	2,56	44,00	21,80	16,89
26G	174,92	385,00	2,71	2,90	44,30	21,60	27,55
27G	106,70	312,08	0,89	1,08	44,10	21,40	20,73
28G	141,74	306,58	0,96	1,15	44,10	21,30	28,16
29G	142,49	266,46	0,96	1,18	44,10	21,10	28,37
30G	173,24	267,95	0,35	0,62	44,10	20,80	28,32
31G	107,92	267,30	0,30	0,51	44,50	20,50	23,42
32G	106,74	161,72	0,80	1,15	44,60	20,00	23,54
33G	175,10	160,69	1,18	1,42	44,70	19,60	57,84
34G	141,49	156,37	0,87	1,15	44,60	19,20	41,66
35G	141,22	42,81	0,36	1,15	44,50	19,00	54,04
36G	174,93	43,89	0,09	0,93	44,50	18,60	62,37
38G	107,27	42,41	0,56	1,16	44,50	18,00	56,70
39G	142,81	391,94	1,75	2,00	43,40	17,30	19,31
40G	142,23	310,14	1,42	1,65	43,70	17,30	26,72
41G	108,95	307,64	1,02	1,15	44,00	19,20	34,29
42G	108,60	270,74	1,80	2,00	44,40	19,10	25,75
43G	176,96	269,90	2,19	2,44	44,40	18,70	34,21

Nº	Air flow (Nm³/h)	Volume flow (L/min)	Liquid in (ºC)	Liquid out (ºC)	Air in (ºC)	Air out (ºC)	Efficiency (%)
44G	143,56	270,40	2,30	2,49	44,40	18,40	36,87
45G	143,75	164,01	1,17	1,41	44,30	18,10	48,56
46G	177,42	159,49	0,48	0,80	44,40	17,80	46,93
47G	109,03	160,25	0,07	0,34	44,50	17,30	34,79
48G	108,81	43,06	0,43	0,98	44,50	16,70	64,82
49G	178,60	42,82	0,66	1,42	44,60	16,20	79,10
50G	140,79	43,44	0,61	1,36	44,70	15,90	63,16

When represented in graphic form, each one of these experiments shows a very similar distribution. Three of these graphs can be seen here:

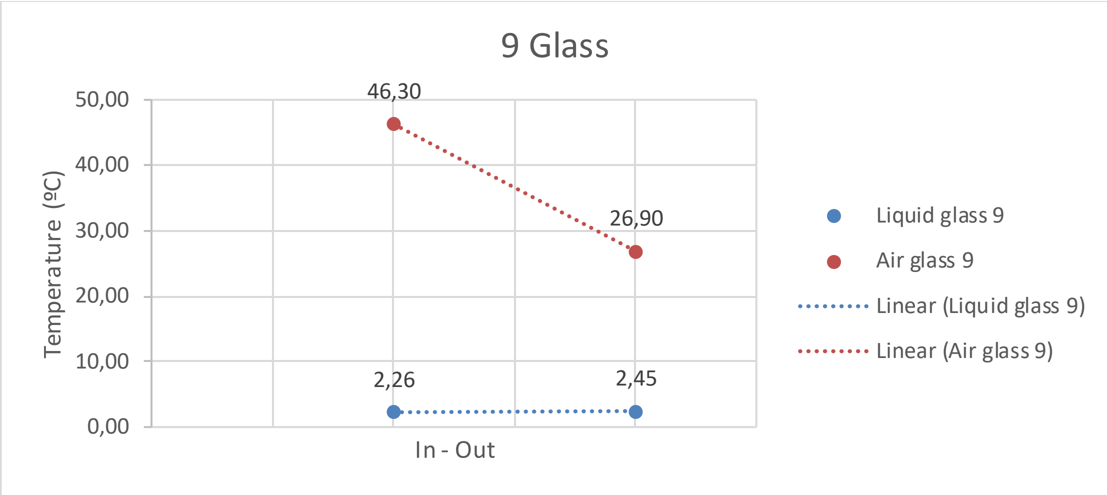

Figure 6. In-out temperatures in experiment 9

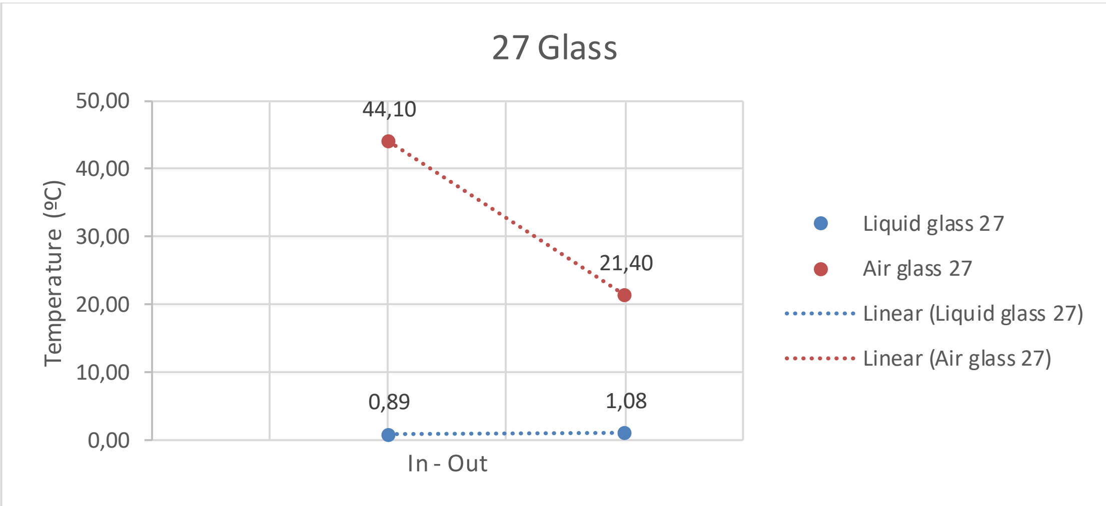

Figure 7. In-out temperatures in experiment 27

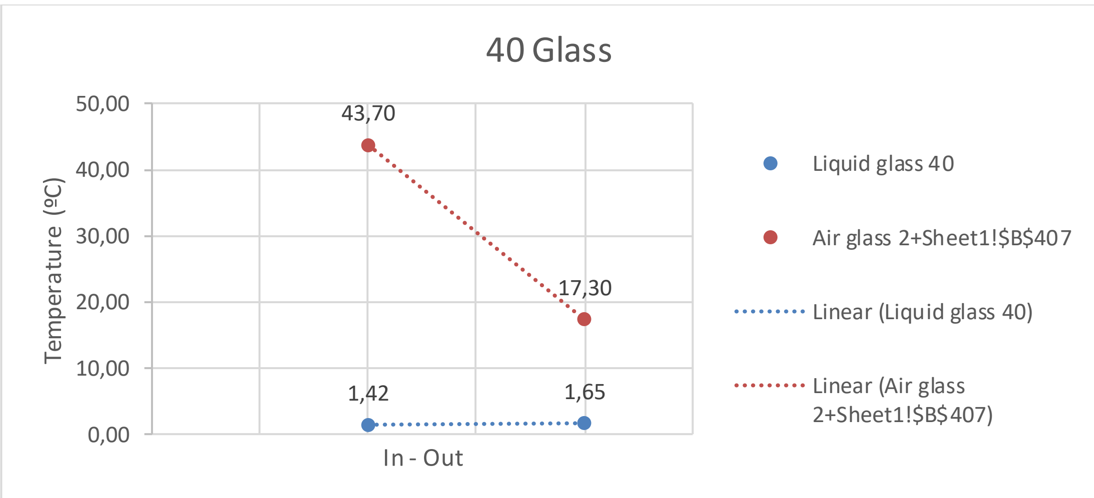

Figure 8. In-out temperatures in experiment 40

As noted before, the representation takes an almost identical form in each of these graphs, meaning the behaviour of the system is consistent throughout the research conducted. For what can be inferred from the graph, there is a slight increase in liquid temperature while the decrease in air temperature is much more noticeable. This is due to the energy transferred from the liquid to the gas, the latter having a much smaller specific heat.

From the tables there is another relation that can be extracted. There seems to be a direct relation between the ratio of liquid flow and the efficiency of the system:

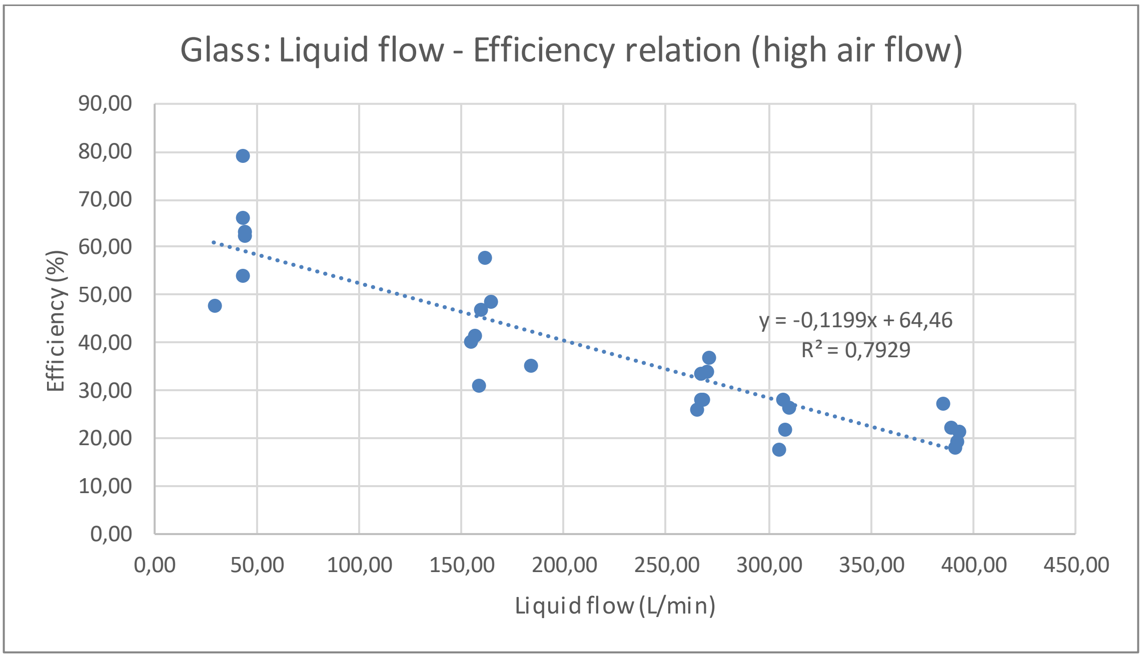

Figure 9. Correlation between liquid flow and efficiency of the system with high air flow

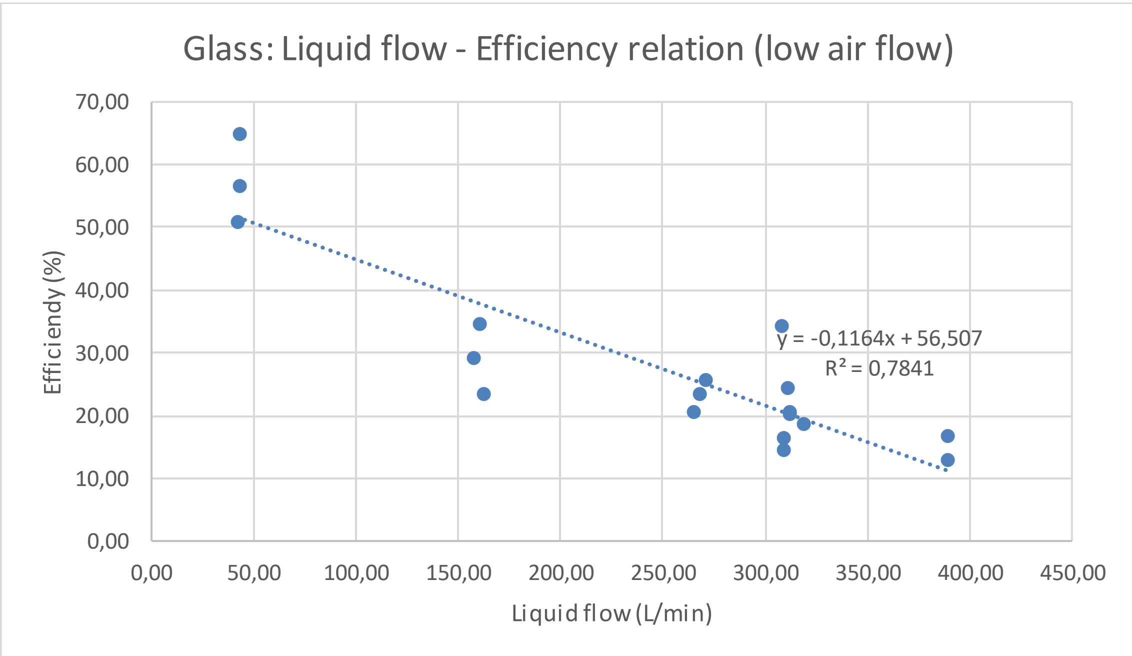

Figure 10. Correlation between liquid flow and efficiency of the system with low air flow

High distribution of the results makes for a poor correlation on the tendency line, but the behaviour seems clear. In both cases, high or low flow of air current, the more the liquid flow is increased we get a higher efficiency parameter value, meaning the exchange of energy between both fluids is more efficient. This means a better use of the energy used in the process, and could bear interesting applications for industrial purposes in practical cases.

Silicon carbide

A total of 41 experiments have been conducted using the silicon carbide pipes. A table containing all the experiments is presented next, excluding the ones discarded:

Table 2. Experiments conducted with silicon carbide pipes

Nº	Air flow (Nm³/h)	Volume flow (L/min)	Liquid in (ºC)	Liquid out (ºC)	Air in (ºC)	Air out (ºC)	Efficiency (%)
4SiC	*106,39*	*258,27*	*4,22*	*4,23*	*30,70*	*26,90*	*79,44*
6SiC	*107,50*	*330,82*	*4,79*	*4,84*	*45,90*	*29,40*	*54,42*
7SiC	*167,54*	*326,69*	*5,13*	*5,18*	*46,30*	*28,90*	*90,58*
9SiC	*107,82*	*146,67*	*0,61*	*0,75*	*46,30*	*28,30*	*47,97*
10SiC	*106,55*	*260,80*	*0,41*	*0,51*	*46,20*	*28,20*	*37,32*
11SiC	*104,15*	*330,92*	*0,90*	*0,98*	*45,90*	*26,50*	*38,73*
14SiC	*166,58*	*263,15*	*0,25*	*0,35*	*45,30*	*25,70*	*62,97*
15SiC	*165,52*	*109,72*	*1,17*	*1,49*	*44,70*	*25,20*	*46,66*
17SiC	*164,84*	*27,26*	*1,06*	*1,82*	*44,00*	*24,10*	*80,36*
18SiC	*104,86*	*260,71*	*0,93*	*1,00*	*44,30*	*20,70*	*68,82*
19SiC	*139,36*	*263,72*	*1,69*	*1,81*	*44,30*	*20,90*	*52,30*
20SiC	*140,39*	*147,33*	*1,46*	*1,61*	*44,70*	*20,60*	*77,70*
21SiC	*103,82*	*145,12*	*1,10*	*1,28*	*44,70*	*20,60*	*48,61*
22SiC	*169,53*	*146,68*	*0,89*	*1,04*	*44,70*	*20,30*	*95,42*
23SiC	*169,72*	*41,21*	*0,41*	*1,15*	*44,60*	*20,10*	*69,20*
25SiC	*136,81*	*39,64*	*0,12*	*0,76*	*44,50*	*19,40*	*68,70*
26SiC	*139,73*	*328,33*	*1,21*	*1,29*	*43,70*	*17,30*	*71,28*
27SiC	*140,29*	*264,96*	*0,60*	*0,69*	*44,00*	*17,40*	*79,42*
28SiC	*103,47*	*263,98*	*0,42*	*0,51*	*44,10*	*17,40*	*59,02*
29SiC	*101,09*	*143,43*	*0,25*	*0,39*	*44,30*	*17,40*	*68,73*
30SiC	*166,31*	*148,40*	*0,96*	*1,21*	*44,30*	*17,50*	*60,97*
31SiC	*137,87*	*143,80*	*0,98*	*1,15*	*44,30*	*17,40*	*77,00*
32SiC	*137,35*	*40,23*	*0,41*	*1,03*	*44,40*	*17,10*	*76,30*
33SiC	*167,20*	*39,52*	*0,08*	*0,75*	*44,50*	*16,70*	*89,09*
34SiC	*101,91*	*38,54*	*0,08*	*0,52*	*44,40*	*16,60*	*84,79*
35SiC	*141,10*	*38,31*	*0,00*	*0,64*	*44,60*	*14,80*	*87,04*
36SiC	*105,40*	*146,40*	*0,29*	*0,45*	*44,80*	*14,30*	*69,65*
37SiC	*105,02*	*41,54*	*0,41*	*0,91*	*45,10*	*14,10*	*79,55*
39SiC	*139,11*	*146,53*	*0,23*	*0,48*	*44,20*	*13,70*	*58,78*

When represented in graphic form, the resulting distribution in each look very similar to the case with glass pipes. Here some of the graphs are presented:

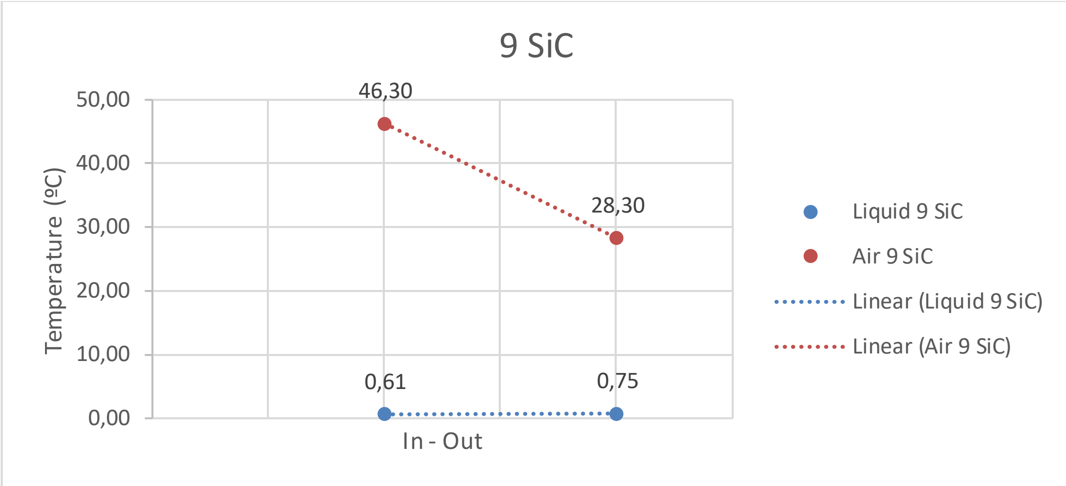

Figure 11. In-out temperatures in experiment 9

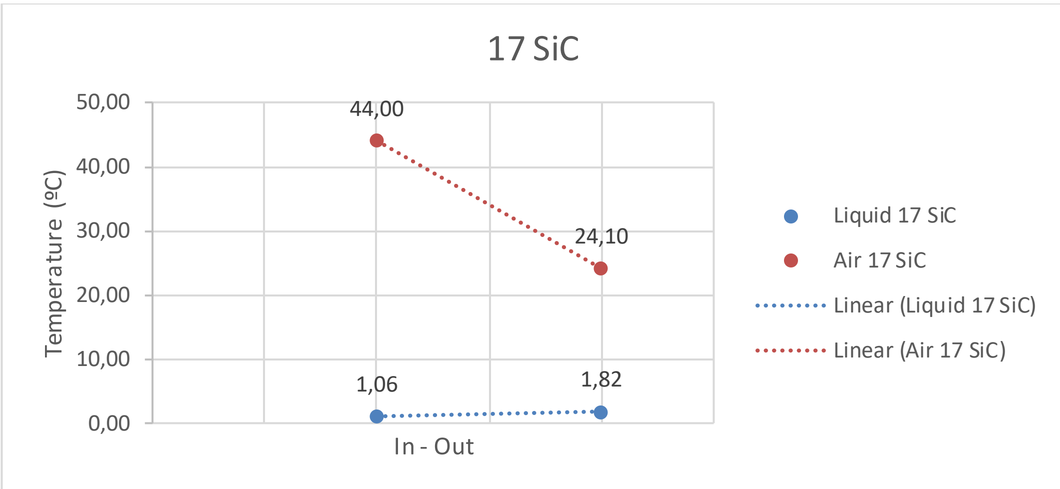

Figure 12. In-out temperatures in experiment 17

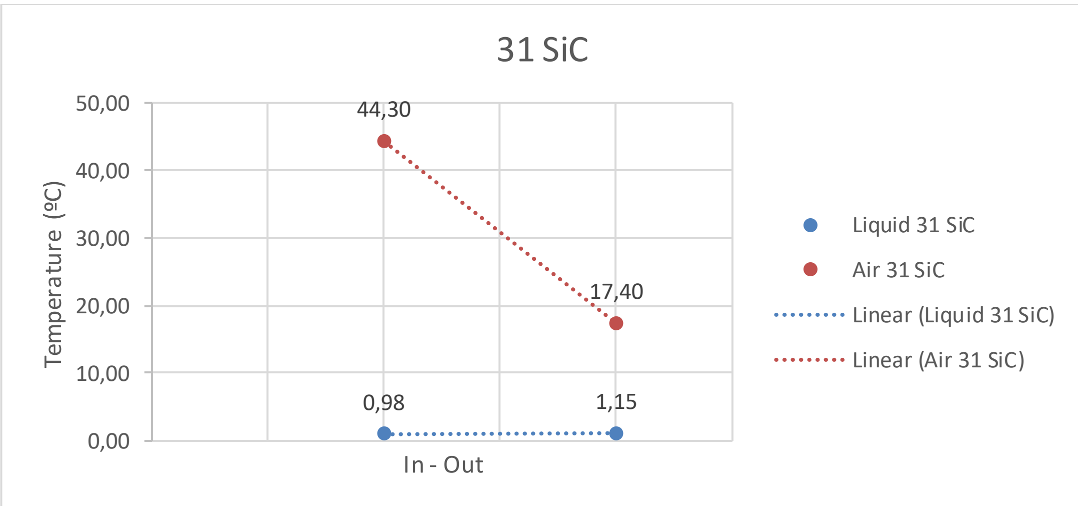

Figure 13. In-out temperatures in experiment 31

As is the case with the glass pipes, all the experiments present a very similar form to the ones presented here, assuring the constant behaviour of the system. Despite this, there is a major difference in the use of this material if compared to the one conducted with glass pipes, and it is the lack of correlation between the flow ratio and efficiency of the system. If tried to represent this relation as in the case before, the graph takes the following form:

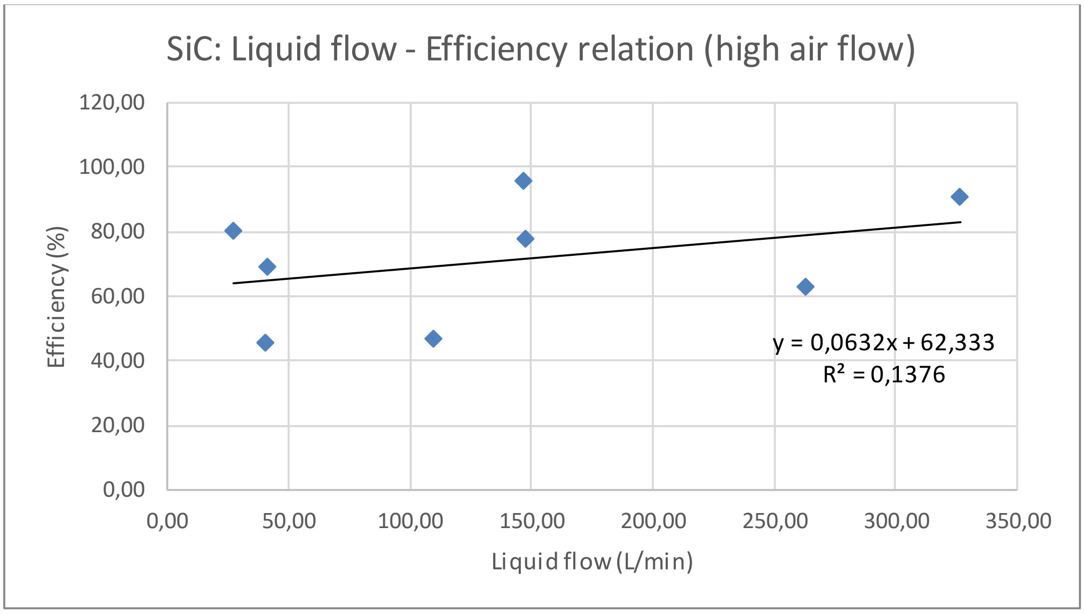

Figure 14. Correlation between liquid flow and efficiency of the system with high air flow

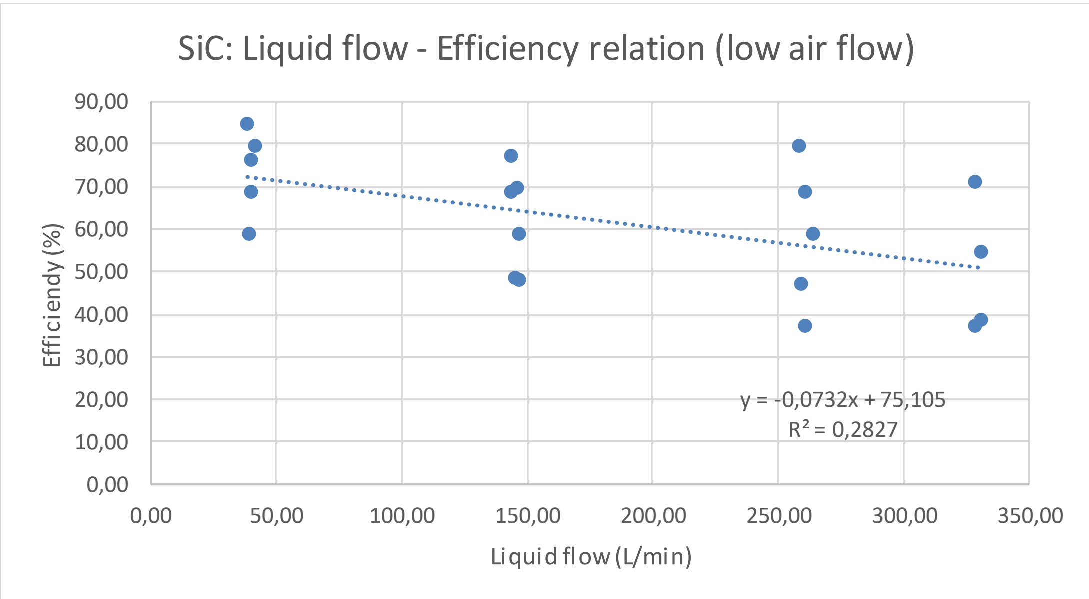

Figure 15. Correlation between liquid flow and efficiency of the system with low air flow

In the case of high air flow, no direct relation between the two parameters can be observed, this being one of the main differences between the 2 systems. On the other hand, with low air flow there seems to be a very faint tendency towards the same behaviour observed in the first case (glass pipes), although the data does not appear to be enough to confirm this theory.

Discussion

After processing all the data, we get an average value of the efficiencies in each system as follows:

Table 3

Average efficiency (%)	
Glass	34,24
SiC	63,80

This means that concerning the amount of heat transferred with success the silicon carbide is a much better option as a layout for the system, because a lot less energy is lost in the process. This is due to the carbide being a much better conductor, allowing for a better transfer of energy between fluids. This raises other problems, as the price difference between both components is noticeable, and in applications where long tubes are required this could represent a cost problem.

Referring to the initial objectives, in the glass experiment the liquid flow has been found to be the parameter which bears a biggest influence in the outcome of the experiment by a huge margin. Reducing the liquid flow levels meant a really big increase in efficiency, much more noticeable than with air flow levels, flow speed or initial temperature of the inlets. This is likely to be due to the liquid spending a bigger amount of time in the tubes and having a bigger effective surface of contact with the hot fluid.

On the other hand, this relation cannot be observed in the sili con carbide scenario, where there does not seem to be a parameter with a direct influence on efficiency of heat transfer, although the value of this efficiency tends to be much higher than in the previous case. This is since the carbide is a much better conductor, allowing for a much faster energy transfer with less losses.

Per setting an optimal set of conditions to get to the maximum achievable efficiency concerning the heat transfer, in the case of glass tubes it seems that the best results are conditioned to a small liquid flow rate, as presented in figures 9 and 10. This does not seem to be the case for the silicon carbide tubes, and no set of optimal conditions could be achieved due to the high variation in the efficiency parameter.

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